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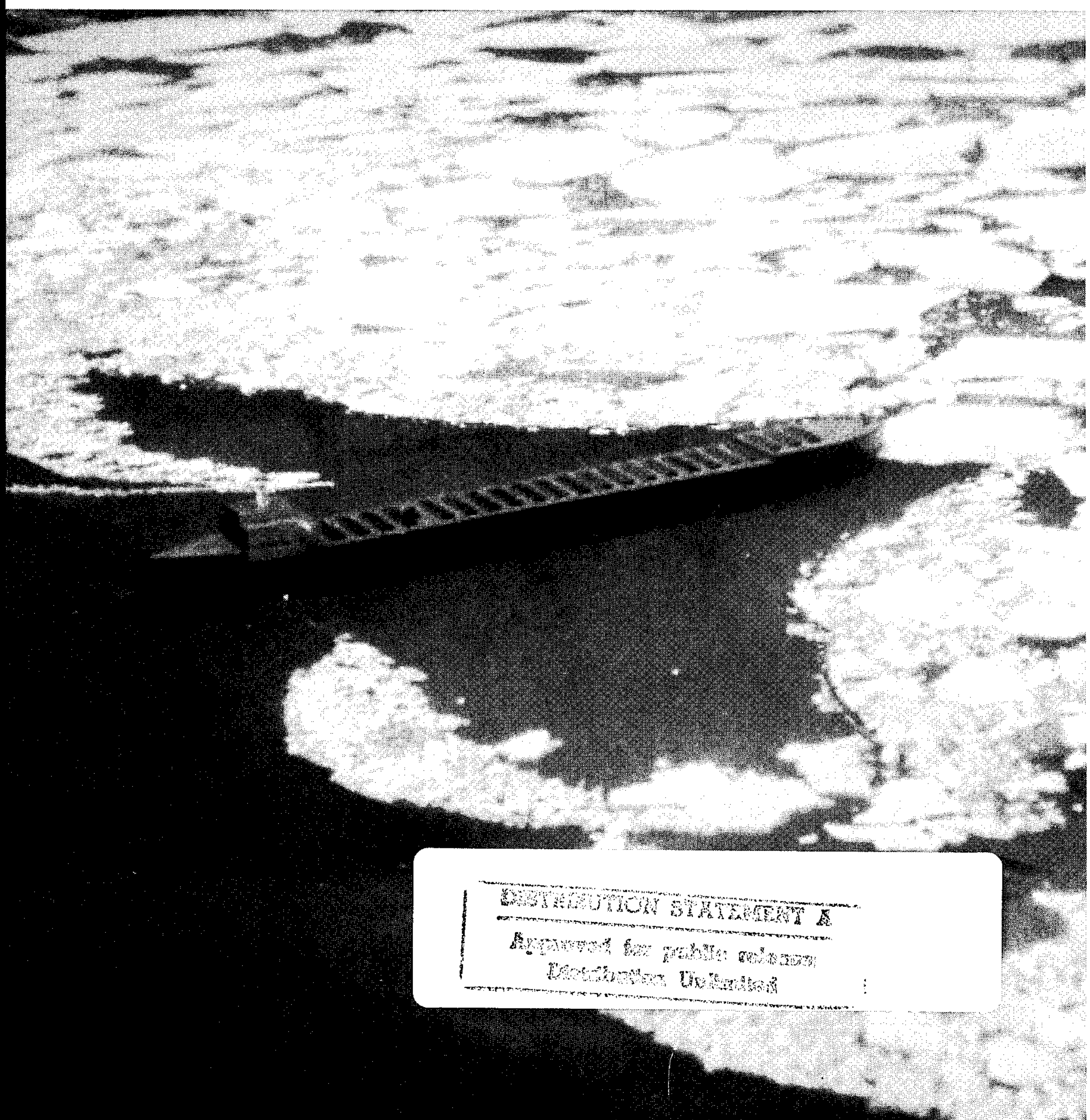
Model Ice Properties

Jon E. Zufelt and Robert Ettema

February 1996



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Abstract
Physical modeling is often used to study complex ice processes when analytical formulations or numerical simulations fall short. Judicious choice and use of materials to model the ice in scaled experiments requires knowledge of the properties of the material as well as an understanding of the dominant forces governing the process to be modeled. This report describes general similitude requirements for various modeling situations and the properties of several previous and currently used model ice materials.

Cover: Physical model simulation of ship transit through broken ice.

For conversion of SI units to non-SI units of measurement consult *Standard Practice for Use of the International System of Units (SI),* ASTM Standard E380-93, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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Cold Regions Research & Engineering Laboratory

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PREFACE

This report was prepared by Jon E. Zufelt, Research Hydraulic Engineer, of the Ice Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), and Dr. Robert Ettema, Professor and Research Engineer with the University of Iowa's Iowa Institute of Hydraulic Research (IIHR) while on sabbatical at CRREL. The project was funded by CWIS, Work Unit 32691, *Model Studies of Ice Jams*.

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INTRODUCTION

Physical models have long been used to study complex natural processes not readily amenable to analytical formulation or numerical simulation, or whose variables of interest are difficult to measure in the prototype system due to size, areal extent, and personnel safety. Ice-cover formation, evolution, jamming, and failure can be so categorized. They are intrinsically messy, three-dimensional, and unsteady processes. Moreover, they often are difficult to observe, especially from the shoreline, because some parts of the process occur out of view beneath the ice surface.

The first use of a material to model natural ice behavior in scale physical models dates back to 1918 when blocks of paraffin wax were used to model ice movement on flowing water (USDI 1980). Paraffin blocks were also used in 1949 for the first reported model of ice jamming on the St. Francis River near Bromptonville, Quebec (FENCO 1949). Since then, many alternative materials have been developed and adapted for use as model ice in physical models of diverse ice processes. Wuebben (1995) gives a good history of physical models used to study ice jamming processes.

This report is a compendium of information on the types and appertaining properties of model ice materials used in physical modeling. It begins with a brief summary of the processes commonly modeled, then reviews the similitude criteria for replicating those processes. The remainder of the report discusses the properties and effectiveness of various model ice materials.

ICE PROCESSES

In addition to the dynamics of water movement, as well as structural loading and response, ice modeling may involve any of the following processes: ice-piece buoyancy; the two-phase (liquid–solid) dynamics of ice motion; the strength and deformation behavior of ice, as monolithic ice pieces and as particulate accumulations of ice pieces; and friction between ice pieces, between water and ice in its various forms, and between ice and materials against which it rubs. Ice modeling may, in certain situations, need to take into account thermodynamic processes associated with ice growth and ice properties, especially ice strength.

Though most modeling situations involve several concurrent processes, it may not be possible to fully simulate them all. Even in relatively simple situations involving simple processes, such as single-phase flow of water in an open channel, full similitude is seldom achieved. In virtually all modeling situations it is necessary to identify the processes of prime importance, to recognize the forces that dominate them, and then to scale the model and select a model ice to maintain, as closely as practicable, the same ratios between these forces in the model and at full scale.

Ice modeling usually falls into two general categories: ice-transport (hydraulic) modeling and ice-load modeling. For hydraulic modeling, similarity of water flow, ice movement, and ice accumulation are of primary importance. For ice-load modeling, similitude of ice forces exerted during ice–structure or ice–ship interaction, ice strength, ice-piece movement around structures and hulls, friction between ice pieces, and ice piece size are of primary importance.

Thermodynamic processes are very difficult to simulate at small scale in a physical model. For example, the entire process of ice growth and formation that accompanies river freeze-up is very difficult to replicate in a small-scale model. Replication of the complex strength and deformation behavior of accumulated ice pieces requires especially innovative modeling techniques when the

full-scale behavior of ice is subject to interpiece freeze-bonding.

Table 1 lists common ice processes treated by means of physical modeling and indicates the important variables influencing them. Model veracity depends on the accuracy with which the model replicates those variables. Note that some modeling situations may involve a combination of processes. Consequently, the variables may be grouped differently than in Table 1.

SIMILITUDE CRITERIA

Similitude criteria prescribe the quantitative relationships between model and full-scale values of variables. For complete similitude, a model must satisfy geometric, kinematic, and dynamic similitude criteria, which usually are stated as dimensionless parameters whose values should be the same at model and full scales. The model ice material is chosen in accordance with the similitude criteria.

Geometric similarity relates full-scale, or prototype, linear dimensions L_p and model dimensions L_m by a length scale λ_L; i.e.,

$$\frac{L_p}{L_m} = \lambda_L. \quad (1)$$

Kinematic similarity requires constant proportionality of prototype and model periods and velocities. In other words,

Table 1. Ice processes and important variables to be modeled.

Ice process to be modeled	*Variables of importance*
Hydraulic models	
Stage increase due to ice	roughness of underside of cover
	ice thickness
	water velocity profile
Ice transport	ice thickness
	ice concentration
	water velocity
	ice velocity
	ice–shore frictional resistance
Ice accumulation/jamming	water velocity
	ice velocity
	ice piece size
	ice concentration
	ice–shore frictional resistance
	angle of internal friction of ice material
	coefficients of lateral pressure, passive pressure, friction
Ice-cover breakup	ice-cover strength
	water velocity
	ice-cover velocity
	cover–shore attachment
	river discharge hydrograph
Ice load models	
Ice sheet deflection	ice-cover flexural strength
	modulus of elasticity
	loading rate
	ice thickness
Ice ridging	velocity of ice sheet
	ice thickness
	ice–ice friction
	ice cover strength (flexural, crushing, shear)
Ice–structure interaction	structure stiffness
	velocity of ice sheet
	ice thickness
	ice-cover strength (crushing, flexural, shear)
	ice–ice and ice–structure friction
	mode of breaking (crushing, flexure, shear)
Icebreaker modeling	vessel speed
	ice–ice and ice–hull friction
	ice thickness
	ice-cover strength (crushing, flexural, shear)
	ice piece size
	piece movement around hull and propeller
	mode of breaking (crushing, flexure, shear)

$$\frac{T_p}{T_m} = \lambda_T \tag{2}$$

and

$$\frac{V_p}{V_m} = \lambda_V = \frac{\lambda_L}{\lambda_T}. \tag{3}$$

Ice modeling usually requires consideration of water movement, ice movement, and ice deformation and failure. The present discussion begins with a brief review of the criteria for dynamic similitude of water flow and ice-piece transport, then reviews the similitude criteria for ice-sheet deformation and failure and the criteria for the deformation and failure of ice rubble. The criteria for ice-sheet, or rubble, deformation are less well developed or generally accepted than are the criteria for water flow and ice-piece transport.

Modeling complexity and the constraints on model ice selection increase markedly with modeling situations requiring that both hydraulics and ice deformation criteria be met. Some modeling situations require consideration only of the similitude criteria associated with water flow and ice-piece transport. For those situations, an unbreakable model ice of appropriate buoyancy suffices. Other modeling situations involve ice deformation in static water and require satisfaction of the criteria for ice deformations and failure as well as for ice-piece movement. Those situations require a model ice that deforms and breaks appropriately. Modeling becomes complicated when the modeled situation requires simulation of water flow as well as the failure and transport of ice. When thermodynamic processes are important, thermodynamic similitude criteria guide the modeling, and the skill of the modeler becomes vital. Generally, the more criteria to be met, the less accurate is the modeling, and greater reliance must be placed on the experience and interpretive abilities of the modeler.

For more detailed coverage and discussion of the similitude criteria see Ashton (1986), ITTC (1987, 1990, 1993), and Ettema et al. (1992).

Water flow and ice-piece transport

Dynamic similarity relates prototype and model forces by a force scale; i.e.,

$$\frac{F_p}{F_m} = \lambda_F. \tag{4}$$

As the scale for mass is

$$\lambda_m = \lambda_\rho \lambda_L^3 \tag{5}$$

in which λ_ρ is the density scale, the acceleration scale is

$$\lambda_a = \frac{\lambda_F}{\lambda_m}, \tag{6}$$

or from velocity and time,

$$\lambda_a = \frac{\lambda_L}{\lambda_T^2}. \tag{7}$$

The force scale can then be expressed as

$$\lambda_F = \frac{\lambda_L^4 \lambda_\rho}{\lambda_T^2}. \tag{8}$$

All dynamic quantities can be expressed in terms of the length, time, and density scales.

Most hydraulic processes are governed by momentum balances involving inertial, gravitational, and viscous forces. Surface tension forces usually are insignificant, except when considering very shallow flows or the movement of small ice pieces. The relative influences of inertial and gravitational forces can be expressed nondimensionally as a Froude number,

$$Fr = \frac{V}{\sqrt{gy}} \tag{9}$$

or as a densimetric Froude number,

$$Fr_D = \frac{V}{\sqrt{gy(\rho_s - \rho)/\rho}} \tag{10}$$

in which V is a representative velocity, y is flow depth or an alternate length of interest, and ρ_s and ρ are solid and fluid densities, respectively. The relative influences of inertial and viscous forces can be expressed nondimensionally as a Reynolds number,

$$Re = \frac{Vy}{\nu} \tag{11}$$

in which ν is the kinematic viscosity of the fluid (usually water). The relative magnitudes of inertial and surface-tension forces can be expressed nondimensionally as a Weber number,

$$W = \frac{V}{\sqrt{k/\rho y}} \tag{12}$$

in which k is the surface-tension strength of water.

Maintenance of the values of Froude, Reynolds, and Weber numbers for model and prototype is the underlying basis of similitude for hydraulic modeling. However, explicit simultaneous satisfaction of Froude, Reynolds, and Weber number similitude criteria is impractical when water is the model fluid as well as the prototype fluid. For water systems modeled using water, the criteria collide: Froude number similitude requires that the velocity scale $\lambda_V = \sqrt{\lambda_L}$, which leads to Reynolds number similitude giving the kinematic viscosity scale $\lambda_\nu = \lambda_L^{1.5}$. Since inertial and gravitational forces dominate free surface flow, the Froude number is used as the principal similitude criterion, and the Reynolds criterion is relaxed by only requiring that fully turbulent flow be maintained in the model. For free surface flow conditions, the transition between smooth and fully turbulent flow (where viscous forces become negligible) occurs at a Reynolds number (based on the hydraulic radius) of 500 to 2000. For ice-covered flow, this value is approximately halved due to the halving of the hydraulic radius with the addition of the ice cover.

From the Weber number (if Froude similitude holds), the scale for surface tension is

$$\lambda_\psi = \lambda_L^2 \lambda_\rho , \tag{13}$$

which shows that, if λ_ρ is held as unity, surface tension must be greatly reduced. This requirement is very difficult to meet, especially when plastic is the model ice, as plastic typically produces more surface tension than natural ice. A relaxation of the requirements for the Weber number can also be made as long as the influence of surface-tension forces remains small compared to inertial and gravitational forces. This is almost always the case in natural systems. In open-water models, surface tension can be assumed to be negligible when depths of 30 to 50 mm are maintained. For ice-covered models, however, surface tension may become a concern, depending on the model ice material used. This concern is discussed under *Model Distortion* below.

Ice-sheet loading

The strength and deformation properties of monolithic ice sheets are of primary interest for modeling ice-sheet loading. Modeling requires a model ice that not only satisfies buoyancy and frictional requirements, but that also deforms and fails in the manner that dominates ice behavior at full scale. Considerable judgment and experience are needed when modeling many ice-load situations, because the full-scale conditions of ice loading and material behavior of ice are complex, still ill-defined, and subject to scientific discussion.

The important failure modes are flexure, shear, and crushing. All three modes may occur simultaneously during ice–structure or ice–ship interaction, though one mode usually dominates. The waterline shape of a structure or ship and contact conditions, together with the strength and thickness properties of an ice sheet, determine which mode dominates. The most common dominant mode for hydraulic failure of ice sheets is flexure caused by change in the water-surface profile of a flow or shoving of ice under or above the sheet. To ensure that model ice deforms in the same manner as ice at full scale, it is customary (e.g., the references given above) to prescribe that the ratio of ice strength σ and elastic modulus E for a particular loading mode be held constant at model and full scales; i.e.,

$$\lambda_{(\sigma/E)} = 1 \tag{14}$$

and that, at both scales, E/σ exceed a minimum value associated with brittle elastic failure. Many modeling guides (e.g., Schwarz 1977, Ashton 1986) stipulate a value of about 2000.

The Cauchy number, *Ch*, is often used as a similitude parameter for prescribing the load and deformation behavior of level sheets of ice. It is a convenient ratio of inertial and elastic forces whose value ideally should be the same in the model and prototype:

$$Ch = \frac{\rho V^2}{E}. \tag{15}$$

Dynamic similitude requires

$$\lambda_{Ch} = 1 = \lambda_\rho \lambda_V^2 / \lambda_E . \tag{16}$$

As water normally is used to replicate water in model studies, and as Froude number equivalence prescribes λ_V, the modulus of elasticity is equal to the length scale for undistorted models: i.e.,

$$\lambda_E = \lambda_L . \tag{17}$$

In accordance with eq 14 and 16, the strength scale equals the geometric scale; i.e.,

$$\lambda_\sigma = \lambda_L . \tag{18}$$

The Froude criterion leads to the same result for scaling stress or pressure (force divided by contact area) when the density scale is unity.

For ice sheet flexure, values of E are estimated typically (e.g., see ITTC 1990) by means of the plate-deflection method, whereby a local load is applied to the ice sheet and the commensurate deflection is measured over an elastic response range. An alternate method is to measure the deflection of ice beams under flexure. From estimated E, together with an assumed Poisson ratio of 0.3 for ice, modelers calculate a representative characteristic length for the ice sheet in flexure. The sheet is treated as an elastic plate, or sometimes a beam, on an elastic foundation. The characteristic length relates plate or beam stiffness to foundation (usually water) stiffness in terms of a load-influence length.

Because ice sheets do not always deform elastically, there is considerable uncertainty as to the significance of Cauchy number constancy as a similitude criterion. Its use is an active subject of debate. Ice may behave as a visco-elastic material whose deformation and failure depend on strain rate. At very low strain rates, creep deformation may occur, whereas brittle elastic failure may occur at high rates. Therein lie several kernels of the debate: thin ice sheets do not deform exactly as thick ice sheets do, and deformation processes may progress at different time scales than a time scale based on the Froude number criterion. Difficulties with model materials are not unique to ice modeling. They also occur when scale-modeling most other two-phase processes, including transport of alluvial sediment and air bubbles. The paramount concern is that the model ice sheet deform and fragment in accordance with the criterion for geometrical similarity while replicating the scaled dominant strength. Ideally, the model ice should produce the same ratio of failure-mode strengths (e.g., compressive to flexural strength) as exists for the full-scale ice.

Accumulations of ice pieces

The strength and deformation behavior of an accumulation of ice pieces, such as forming an ice jam or an ice ridge, are determined by geometric and material factors. Depending on the combination of these factors, the strength and deformation behavior can be relatively simple, or very complicated, to formulate and simulate. Thermodynamic factors, such as freeze-bonding, and material nonhomogeneities, such as local variations of piece size, are difficult to model at small scale.

In comparatively simple situations, the strength and deformation behavior of accumulated ice pieces can be described in terms of accumulation thickness η, porosity p, and angle of internal resistance ϕ. In its simplest state, an ice accumulation can be treated as a floating particulate medium, analogous to a sand, a gravel, or a pile of rocks. The geomechanical relationships for the strength behavior of a particulate medium are applicable to the ice accumulation. Most analyses of ice accumulation behavior adopt this approach.

In nature and in the laboratory, however, the strength behavior of ice accumulations varies as widely as for any particulate material. Individual particles in a particulate continuum are subject to gravity and to electromagnetic force developed between neighboring particles. When the particles are sufficiently large, gravity dominates their movement within the continuum, and the continuum behaves as if it were cohesionless. When the particles are small, the electromagnetic forces between particles dominates, the continuum behaves cohesively, and the character of the individual particle is insignificant. The classic example in this regard is the behavior of alluvial particles, which range from cohesive clays to noncohesive boulders. An analogous range of behavior occurs for ice pieces, though delineation of piece size at which cohesive and noncohesive behaviors dominate is not as well defined for ice pieces. The iceberg or large ice mass lies at one end of the ice-piece size range. At the other end lies the snowflake. Modeling ice mass drift in water, or snow drift in air, entails simulation of ice-piece motion, but at vastly different scales and with strikingly different model ice materials.

The variable strength behavior of an ice-piece accumulation, and thereby of their angle of internal resistance, can be described in terms of a similitude criterion expressing a balance of molecular and gravitational forces. The criterion can be stated as a ratio of molecular or interparticle bond force and ice-piece buoyancy; i.e.,

$$B_o = \frac{P}{\left[\frac{1}{6}\pi(\rho - \rho_i)gd^3\right]} \tag{19}$$

in which P is the sum of interparticle bond forces holding the particle to its neighbors. The denominator is the buoyancy force acting through a particle assumed to be spherical. Accurate estimate of P is difficult. Thus B_0 remains, for the moment,

of qualitative significance and awaits further examination to define a gradation of values to indicate the range of ice-particle behavior. Its use is analogous to the use of a Reynolds number in characterizing the drag coefficients of bodies in moving fluids. In modeling, the aim would be to ensure that the model-scale value of B_o remains within a range of values for which the sticky forces are scaled in correct proportion with the inertial and gravitational forces. Order-of-magnitude estimates can be made for B_o, however. As it approaches zero, an ice-piece accumulation behaves as if it were a cohesionless assemblage of discrete pieces; buoyancy dominates. When B_o exceeds about 10^6, the accumulation behaves as a fused structure of connected particles. At the extreme, the accumulation becomes monolithic ice. The important message here is that it may not be possible to use ice to model ice, because fine-sized ice pieces do not behave like large ice pieces, just as clay does not behave like gravel.

The geometric factors affecting accumulation strength are fairly straightforward to identify and to scale. They include accumulation thickness, accumulation porosity, size and size distribution of ice pieces comprising the accumulation, and shape and roughness of constituent ice pieces. It is much less straightforward to scale the material factors, which include strength and deformation properties of constituent ice pieces and the temperature of ice pieces. All of the aforementioned variables affect the angle of internal resistance of an ice accumulation. Ice-piece size also affects the strength and deformation properties of ice pieces.

The lateral distribution of stress through an accumulation, and the friction of accumulated ice pieces against other surfaces, are additional properties to be taken into account. Forces attributable to lateral stress and ice friction are important for structures or ships flanked by ice accumulations and for ice-jam formation. The shear force at a slip plane (e.g., along the side of a structure or a river bank) depends on the coefficient of lateral pressure, k_0 (akin to a Poisson ratio), and the coefficient of friction of ice rubbing against itself, ξ, or against some other material forming one side of the plane. The passive pressure coefficient, k_1, relates the maximum internal resistance to the average vertical stress within a material. The parameters k_1, k_0, and ξ can be expressed in terms of the angle of internal friction, ϕ, of the accumulation. In turn, ϕ is related to the shape and size distribution of the ice pieces constituting the accumulation. As a lower-bound estimate, ϕ can be taken as the angle of static repose of the particulate material fully dry or immersed in liquid. For a dry, angular cohesionless material,

$$k_1 = \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right), \tag{20}$$

$$k_0 = 1 - \sin\phi , \tag{21}$$

and

$$\xi = \tan\phi. \tag{22}$$

When ϕ increases beyond about 45°, such that extensive interlocking of ice pieces takes place, eq 21 and 22 become less appropriate for estimating k_0 and ξ. Based on the force balance within an ice cover, Zufelt (1992) shows that the value of an alternate parameter, μ, the internal resistance coefficient of an ice cover, is related to k_1, k_0, and ξ by

$$\mu = k_1 \xi k_0 . \tag{23}$$

Beltaos (1993) has reported values of μ for natural ice jams in the range of 0.8 to 1.6, but these were back-calculated from estimates of jam thickness assuming equilibrium thickness theory. Little work has been accomplished on the interparticle friction of particulate ice pieces, ξ, or the coefficient of lateral pressure of wetted particulate masses, k_0.

MODEL DISTORTION

Practical considerations often make it necessary to relax similitude criteria in order to ensure that the model adequately replicates the dominant process under investigation. Limitations in modeling area or flow capacity commonly constrain the horizontal space, and thereby the horizontal scale, of a model. The necessity for small scale may result in very small model depths, to the extent that viscous and surface tension effects become significant. The remedy is to resort to geometric, or vertical, distortion.

A vertical length scale, β_L, is chosen to keep the viscous and surface tension forces in the model at negligible levels. The resulting model distortion, $D = \lambda_L/\beta_L$, is usually maintained at less than 4 for open-water hydrodynamic models, although no strict limit is set. Care must be taken in determining the appropriate scales for horizontal or vertical forces acting on horizontal or vertical planes. The scales are not the same. Consequently, whereas

vertical distortion is acceptable for many hydraulic modeling situations, it must be used with great caution in situations involving ice failure produced by vertical forces and ice loads. Ashton (1986) and Ettema et al. (1992) show, however, that vertically distorted models adequately replicate ice jams, provided the angle of internal resistance of the model ice is the same as at full scale.

In modeling ice-cover breakup or the impact of an ice cover with a structure, some researchers have only considered the strength properties to govern, with the actual thickness of the cover being secondary (Ashton 1986). Michel (1975) suggests using double distortion in which the ice thickness scale is different from the vertical length scale. Model distortion may extend the limits of current model ice materials in replicating prototype ice strengths. Other hydraulic variables besides ice strength that are important in the breakup process include stage, water velocity, and the shape of the inflow hydrograph. Geometric distortion to achieve adequate strength characteristics may cause mismodeling of other important variables.

Besides vertical distortion, other forms of distortion may be used to design a model that replicates the process of primary interest. Among them is time distortion, which becomes important when the modeling situation contains a process that proceeds at a rate independent of the time scale given in eq 2. Fracture development, ice growth, and the downstream migration of wave-like accumulations of ice pieces (analogous to alluvial bedform movement or snowbank drift) are examples of these processes. Model results need careful interpretation in those situations.

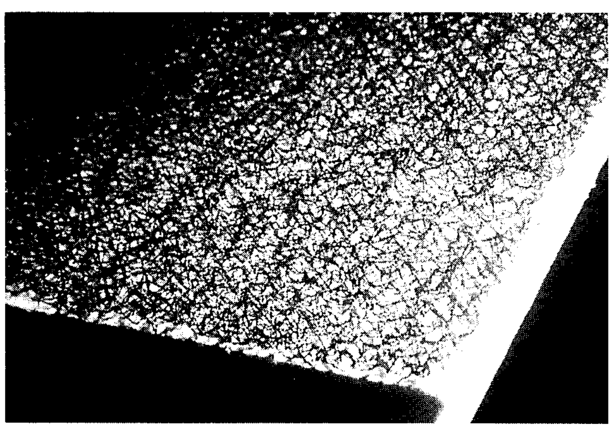

Figure 1. Rigid ice panel showing extruded plastic mesh.

MODEL ICE MATERIALS

The material selected for use as model ice must conform with the purpose and principal similitude criteria guiding operation and interpretation of the model. Thus, model ice materials can be grouped and discussed as follows:

- Unbreakable sheets
- Unbreakable ice pieces
- Ice piece accumulations
- Breakable sheets

Hydraulic modeling and ice-load modeling may involve any of these types of model ice materials. Commonly, though, hydraulic modeling involves unbreakable sheets and ice pieces. Ice-load modeling usually involves breakable sheets and ice pieces that may or may not be breakable. Exceptions exist.

Unbreakable sheets

Unbreakable sheets are used to simulate solid ice boundaries, such as a floating ice cover or large ice masses. The primary dynamic similitude concerns are buoyancy and frictional resistance. Often, provided the model sheet floats, strict replication of ice buoyancy is relaxed when modeling flow in an ice-covered channel. Sometimes the wetting performance of the material is important.

The sheets can be formed from plastic, wood, or Styrofoam or be of composite construction (e.g., a ballasted floating box). They must float on the water surface and move in accordance with the Froude number criterion (for replication of inertial and gravitational forces). Some sheets, such as thin polystyrene or plastic, may be flexible. To replicate flow resistance, additional materials, such as plastic bubble-packing, metal or plastic mesh, horsehair pads, filter cloth, or particulate material, may have to be attached to the sheet. Figure 1, for example, shows a model-ice panel of composite construction, formed from Styrofoam sheets. One side is smooth while the other has a layer of extruded plastic mesh to increase roughness. The panel was used in a study of flow in an ice-covered channel.

Unbreakable ice pieces

Ice-piece modeling falls into two categories: the movement of individual ice pieces, and the aggregation and strength behavior of ice-piece accumulations. Examples of the former category, which is by far the simpler of the two, are ice-mass drift, ice-floe fields, and frazil-floc transport. Examples of the latter category are ice-jams, fields of ice rubble, and ice ridges.

Ice piece movement

The primary dynamic similitude requirements are buoyancy and surface roughness. The requirement for exact replication of buoyancy may be relaxed, as long as the model ice at least floats. Buoyancy similitude is more important for ice pieces than for ice sheets, because ice piece collision and interaction are important processes. Surface tension and surface wetting are more important for ice-piece modeling, too. Real ice usually can be used to model ice, provided both the full- and model-scale ice pieces are sufficiently large that their behavior is dominated by inertial and gravity forces, not interparticle bonding.

Model ice pieces may be cut from sheets of wood, polypropylene or polyethylene plastic, or other floating material. Sheets of plastic are commonly available in thicknesses from a millimeter to about 30 mm and can easily be cut with a band saw.

Unbreakable ice pieces of uniform size may form single-layer accumulations (Fig. 2) that are disproportionately thin and overly strong compared to the accumulations they are intended to replicate. Size uniformity may enable pieces to pack and interlock in a way that may not occur at full scale. Blocky and platey model ice pieces are prone to stack like cards, as shown in Figures 3 and 4. Such stacking is uncommon in nature. Gradation of ice-piece size is important. In addition, ice pieces with large width-to-thickness ratios may break at full scale.

The strength properties of freshwater ice relegate its use to physical process models or strength models at very large scales. The strength of an ice piece can be reduced by tempering (warming the sheet prior to testing) as described below. Zufelt et al. (1993) used polyethylene blocks and fractured freshwater ice to investigate ice passage through a submergible lift gate. The random shape, absence of surface tension, and particle interlocking of the fractured freshwater ice pieces provided more realistic results in ice arch formation. Urroz and Ettema (1987) used both polyethylene and freshwater ice blocks to investigate the shear strength characteristics of floating ice rubble and noted differences in rubble behavior. They attributed the difference between the two materials to the freeze-bonding between the freshwater ice blocks.

Figure 2. A juxtapositioned accumulation of polyethylene blocks.

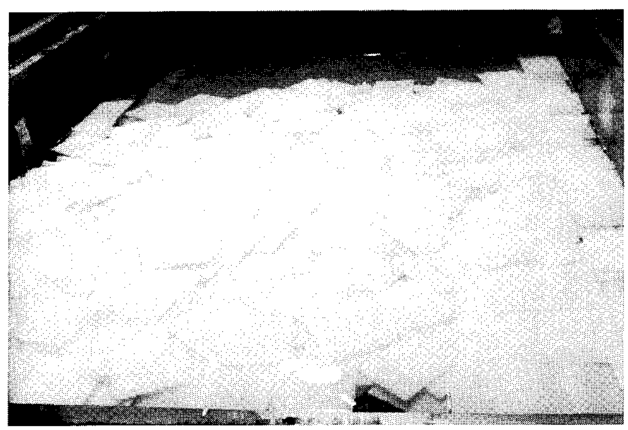

Figure 3. A multilayered ice jam formed of polyethylene blocks.

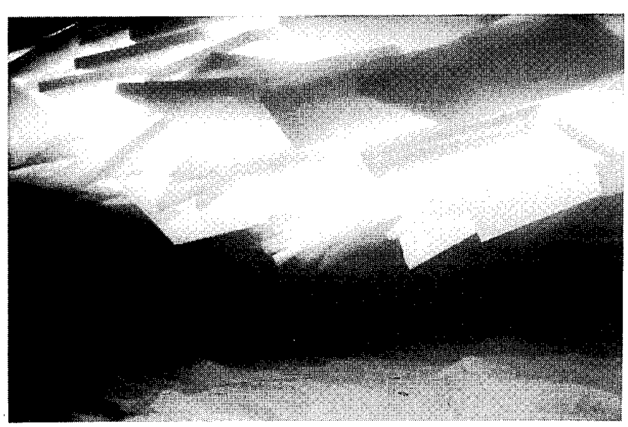

Figure 4. Underside view of an ice jam formed of uniform blocks.

Unlike ice, plastics are nonwetting. Their behavior as model ice may be more greatly influenced by surface tension than is real ice. Surface tension, or nonwetting, is of concern, especially for thin pieces that have negligible freeboard. It may be a factor biasing results in studies on ice-piece submergence and underturning. There are methods to reduce nonwetting, such as adding a wetting agent like nonfoaming detergent to the model water, roughening the surface of the pieces, or allowing a bacterial film to grow on the ice pieces. The latter two methods reduce the size of the meniscus formed by water against a nonwetting surface.

Handling is a practical concern when modeling entails use of a large quantity of comparatively large model ice pieces. Whereas pumps can recirculate water and fine solid material through a model, pieces larger than 10 to 20 mm in diameter may not pass through a pump.

Ice piece accumulations

Of primary importance is dynamic similitude of ice-piece buoyancy, friction, and the angle of internal resistance of the ice-piece accumulation. The hydrodynamic entrainment of pieces from the underside or perimeter of an accumulation may be important for situations where accumulations are formed by flowing water. In many circumstances, small pieces of ice, on the order of 10 mm or less in diameter, may not behave like large ice pieces; a snowflake is not an ice floe, though both are pieces of ice.

For many small-scale models, ice piece accumulation can be replicated satisfactorily using small pieces or beads of polyethylene or polypropylene plastic, to satisfy approximately the requirement for geometric similitude. Ice is suitable as model ice provided it behaves at model scale as it does at full scale; in other words, provided that the "stickiness" of the ice pieces is the same at both scales. Model ice pieces can be cut from plastic sheets, or they can be obtained as pellets used for plastic molding or as fragments of crushed recycled plastic. Polyethylene or polypropylene pellets work well for small-scale models requiring a large quantity of model ice. The pellets are typically spherical or cylindrical with a length of less than about 7 mm. In some circumstances, controlled crushing may produce the size and gradation of pieces needed for a particular model. Figure 5 shows an ice jam model formed of crushed polypropylene. Accumulations of pellets or crushed plastic act as a noncohesive particulate continuum. Their strength behavior conforms to the Mohr-Coulomb failure criterion for granular materials. A further advantage to be gained from pieces of crushed plastic is their high angularity, which gives their accumulations a larger angle of internal resistance than accumulations of pellets. Ice jam initiation or ice arch formation is dependent on the angle of internal friction and interparticle friction characteristics of the model ice material. Materials with a higher angle of internal friction form ice arches more easily. Both the pellets and the fractured material can be obtained in large quantities at reasonable cost.

Dynamic similitude requires that the specific gravity of model ice, and the angle of internal friction of the modeled accumulations, be approximately that of natural ice accumulations. Polyethylene has a specific gravity in the range of 0.915 to 0.925, almost identical to that of natural ice (0.92). The specific gravity of polypropylene is slightly less, at 0.90 to 0.91. The angle of internal friction of model ice can vary widely, depending on the piece shape, angularity, and size distribution. Most model ice materials have angles of internal friction somewhat less than that reported for natural ice accumulations. The fractured materials (due to their highly angular shape and wide size distribution) have the highest angle of internal friction, which approaches that of natural ice. In many situations, scant information exists on the frictional characteristics of ice and model ice in contact with diverse surfaces.

It is common for ice-piece accumulations in nature to consolidate by freeze-bonding or freezing of pore water between ice pieces. Refrigeration may consolidate accumulations of ice pieces used

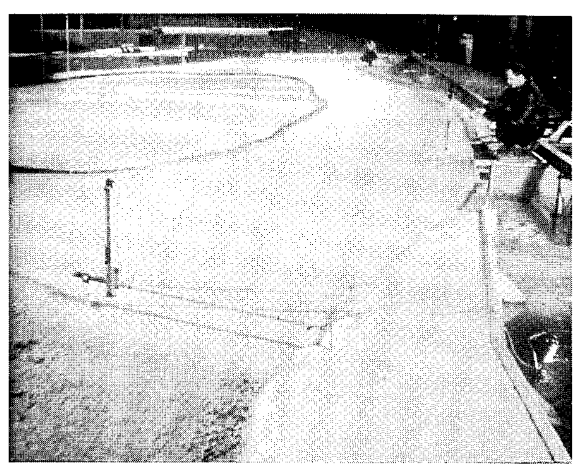

Figure 5. Physical model showing an ice jam formed of particulate material.

to model ice, although the bond strength between pieces may be insufficiently scaled. One means to simulate, at least approximately, consolidation using other materials as model ice is to mix or add some sticky liquid that glues the pieces together. Garbrecht et al. (1981), for example, used polypropylene blocks with a distribution of sizes, shapes, and thicknesses to model a jam on the Elbe River. They consolidated their model ice using a liquid paraffin wax.

Interparticle bonding is a characteristic feature of accumulations of the smallest of ice pieces, snow. Moisture and electrostatic forces between snow flakes cause them to move as particulate agglomerations and enable snow to accrete on diverse structures and snowdrift accumulations to stand with leeward slopes steeper than those of, say, fine sands. The agglomerative, or cohesive, behavior of snow is handled customarily (e.g., Haehnel et al. 1993) using either activated clay or fine-diameter glass beads. The latter material is preferred because the particle size (~3 microns) of activated clay, a powder of refined bentonite clay, makes it hazardous as a potential promoter of silicosis or lung cancer. These days the use of activated clay has been replaced largely by the use of glass beads with diameters in the range of 40 to about 100 μm and specific gravity of 2.44. Thus, as the specific gravity of dry snow is about 0.7, snowdrift modeling relies on densimetric Froude number similitude.

Material handling is fairly easy for small or particulate model ice pieces, because most particulate sizes pass through pumps. The handling difficulty is eased also because particulate model ice can be added to the water inflow at the upstream end of a model with little surface disturbance.

During ice jamming or ice runs there is typically a zone along the shoreline where ice is either frozen to or grounded on the banks. This results in a shear zone with frictional resistance to movement along the banks dependent on the interparticle friction characteristics of the ice material. It is important to maintain similitude of friction forces. Model boundaries should be sufficiently rough so that, as may occur for many rivers, model ice material grounds along the banks and provides a true ice–ice shear zone (Fig. 6). Excess surface tension forces between particles can result in an overreduction of ice velocity. Zufelt et al. (1994) used an air bubbler along one portion of a scale physical model boundary to counter surface tension forces and increase model ice velocities

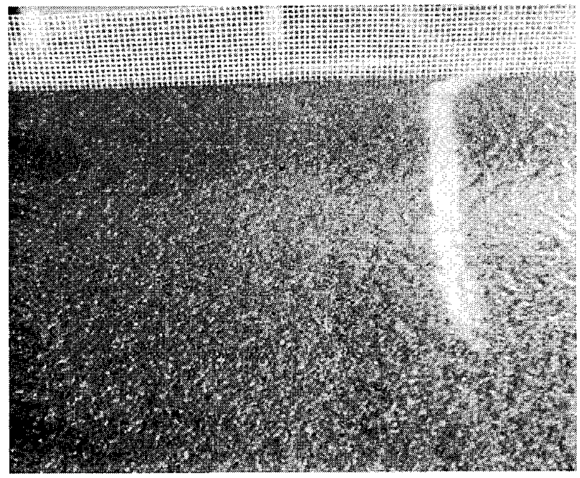

Figure 6. Roughness attached to flume side walls traps ice material and correctly models the ice-on-ice shear zone.

during model calibration.

CRREL's experience with particulate model ice materials includes the use of so-called Iowa beads, CRREL beads, and NYPA ice, a fractured polypropylene material (Fig. 7). Several other materials have been tested in very small quantities to determine their suitability for model studies. Figure 8 gives a close-up view of NYPA ice, CRREL beads, and Iowa beads. Table 2 describes the general physical characteristics of these three model ice materials. The values given in Table 2 for k_1, k_0, ξ, and μ are calculated by eq 20 through 23 and, as can be seen from the NYPA ice values, are probably overestimated. Equations 20–22 are based on dry angular materials and may not hold for wetted plastics. Experimental measurements of the values of these coefficients are currently lacking for both prototype and model particulate ice materials.

Breakable ice

Of primary importance in the consideration of sheets of model ice that are used for investigating ship or structure impact with ice sheets is the dynamic similitude of ice buoyancy, friction, and ice failure mode(s). Real ice with weakening additives may serve as a breakable model ice when modeling in a refrigerated environment. Alternately, when modeling in a nonrefrigerated environment, several nonaqueous materials may serve as a breakable model ice. Modeling practice favors the use of real ice with weakening additives and requires the use of refrigerated laboratories and ice-towing tanks.

There has been a major investment in research-

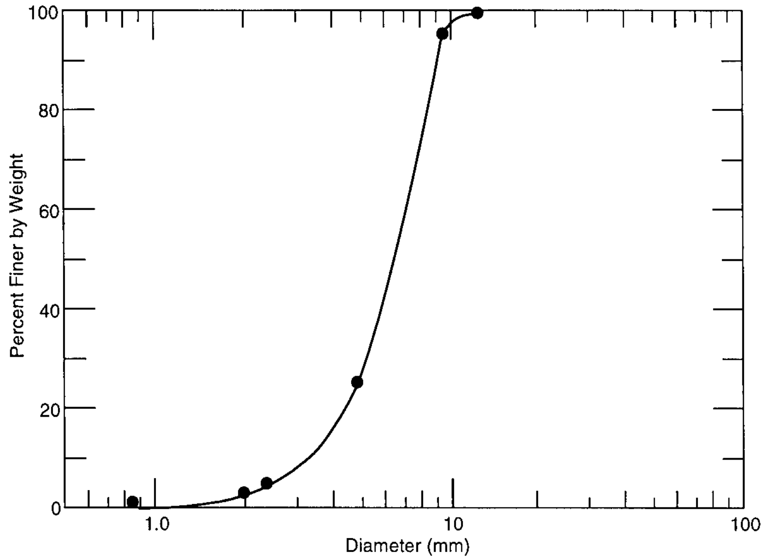

Figure 7. Size gradation of fractured polypropylene model ice material.

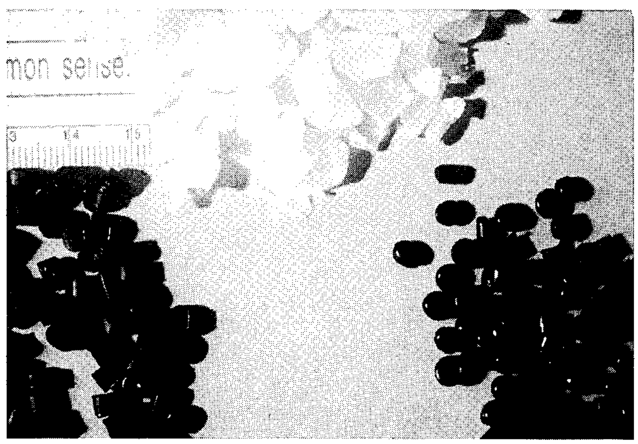

Figure 8. Model ice materials. Top: NYPA ice (polypropylene). Bottom left: CRREL beads (polyethylene). Bottom right: Iowa beads (polypropylene).

Table 2. Physical characteristics of plastic model ice particulates.

Characteristic	*Iowa beads*	*CRREL beads*	*NYPA ice*
Shape	Rods and discs	Squashed cylinders	Angular
Size	$D = 3$ mm	$L = D = 3–4$ mm	$D_{50} = 6$ mm
Angle of internal friction, ϕ	27	34	46
Passive failure coefficient, k_1	2.66	3.54	6.13
Coefficient of lateral pressure, k_0	0.55	0.44	0.28
Static friction coefficient, ξ	0.5	0.67	1.0
Overall, μ	0.73	1.04	1.78

ing and developing breakable model ice materials. An aim of that work has been to produce a model ice that will facilitate small-scale modeling of large structures, vessels, and ships. To date, severe scale limitations have required the use of large and very expensive refrigerated laboratories to accommodate such modeling.

Weakened ice

Most weakened ices are thermally grown. The weakening additives are included in the solution from which the ice is grown, or are added to (e.g., sprayed or sprinkled on) the ice as it grows. Two other weakening techniques are also used. One entails weakening by warming to reduce the

strength of the model ice to a prescribed value commensurate with the model scale. The other is to produce an ice sheet whose crystal structure is amenable to weakening. Therefore, crystal structure, additives, and warming are the three main methods used to prepare a weakened ice to suit a particular modeling situation. Considerable skill is necessary to combine the ingredients and prepare the model ice. The IAHR Working Group on Ice Modeling Materials (IAHR 1992) gives an excellent history of the advances in preparing weakened ice.

Doped ice. Chemically, or solute, weakened ice is often called *doped ice*. A chemical, or dopant, is added to the water before freezing and ice sheet growth. Sometimes several chemicals are added, and they are known collectively as the dopant. An incubation process usually is needed to start the ice sheet so that it forms the required crystal structure. While the ice sheet thickens, the dopant is rejected and trapped in "brine" pockets between the ice crystals, giving the sheet a structure similar to that of sea ice. The presence of these pockets reduces the initial strength of the model ice as compared with that of freshwater ice. Strength properties can be further reduced by warming the sheet, which requires raising the air temperature above the sheet close to the freezing point of the solution from which the sheet is made, thereby tempering the ice sheet. During tempering, the brine pockets enlarge and weaken the ice. During tempering, which may take hours, the sheet's modulus of elasticity E decreases faster than its flexural strength σ_f, so that the ratio E/σ_f also decreases. The common practice is to limit the geometric scale for ice-load modeling with doped ice in accordance with the minimum ice strength that can be attained while ensuring that E/σ_f remains above about 2000. This limit is a subject of debate among ice modelers.

Doped ice was developed originally for modeling ice forces on structures and icebreaker vessels. The earliest doped model ice was grown from a 2% saline solution. For workable length scales of 25 to 40, the saline ice gave E/σ_f ratios much lower than 1000, below the minimum acceptable value of 2000 for sea ice. Schwarz (1977) emphasized the importance of maintaining a high E/σ_f ratio and used a lower concentration (0.6%) saline solution to grow model ice. However, even with tempering, the minimum flexural ice strength achievable was on the order of 60 kPa, significantly greater than that required for a geometric scale of 25 and above. The model test results, therefore, had to be corrected or extrapolated to the proper ice strength, which added another possibility of error and uncertainty in the final test predictions.

ARCTEC Inc. developed and patented a process for rapidly producing ice sheets. In specially designed tank facilities, the air was cooled to about –60°C by spraying liquid nitrogen over the surface of the tank of saline (NaCl) water. The ice was grown at rates up to 10 mm/hour. At this rapid growth rate, a large amount of brine was trapped in the ice, resulting in low ice strengths. ARCTEC built two facilities around this process and tested mainly icebreaker models between 1970 and 1987, even though the process became expensive due to the increasing cost of the liquid nitrogen. Urea dopant was substituted for the NaCl in the later years. No strength data are publicly available for ARCTEC's ice.

Timco (1980) reported producing 40-mm-thick ice sheets, grown from a 1.3% carbamide (urea) solution, with an E/σ_f ratio of 2400 for flexural strengths as low as 20 kPa. However, Hirayama (1983) reported that, for 20- to 25-mm-thick ice, the E/σ_f ratio could be on the order of 1000 or less. The carbamide-doped ice was very similar in structure to the saline ice (Fig. 9), due to the growing procedure (Gow 1984). For both ice types, the water surface is seeded with a fine mist, resulting in a fine crystalline pattern on the surface. The ice cover then grows thermally with vertical, columnar crystals extending down into the water. The resulting ice could be considered to be two-layered: a strong congelation upper layer over a weaker

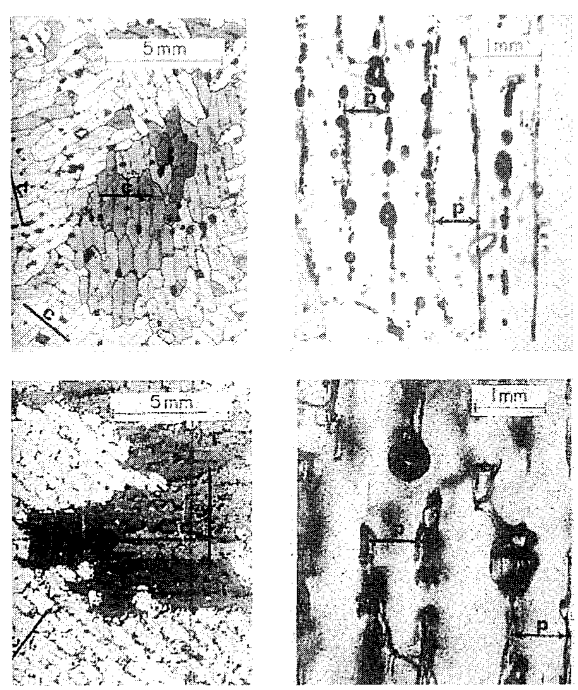

Figure 9. Comparison of size of crystals and brine pockets in urea-doped ice (top) and sea ice (bottom).

lower layer (Fig. 10). This variation in structure over the ice thickness results in nonhomogeneity of the mechanical properties of the ice, so care must be taken when reporting results of how tests were conducted and how measurements were made. The thickness of the upper congelation layer can be minimized by seeding and growing the ice sheet at the lowest temperature that can be achieved.

While saline-doped ice appears not to have been used for hydraulic modeling, urea-doped ice has been used with success in many hydraulic model studies. Deck (1985) used urea-doped ice to reduce the strength of a model ice sheet in a study of a breakup ice control structure. He was able to properly scale the ice strength even though he found it necessary to introduce a distortion of 4 to provide adequate model depths and reasonable model ice thicknesses.

EG/AD/S ice is a model ice material that was developed at the Hydraulics Laboratory of the National Research Council of Canada with the goal of producing a model ice that would be single-layered and columnar in structure; i.e., the model ice would not include a congelation layer. Timco (1986) reviews the requirements for the new ice material and describes how the EG/AD/S combination of chemical dopants was selected. The three dopants are ethylene glycol, aliphatic detergent, and sugar; hence the name EG/AD/S. This weakened ice produces flexural strength and E/σ_f ratio values that are very close to those of urea-doped ice, but it reputedly has more realistic fracture-toughness performance, and thus cracking replication, because it is nearly single-layered (Fig. 11).

A problem with doped ices is their disproportionately large brine content for low strength conditions. The criteria for buoyancy similitude may not be met, because the model ice is denser than ice at full scale. Spencer and Timco (1990) describe a method to incorporate minute air bubbles into a growing ice sheet, thereby controlling its overall density. They refer to this ice as controlled density (CD) ice. They can reduce ice sheet densities to specific gravity values of 0.83 to 0.93 by adding microbubbles at various times during the growth of the ice sheet. They report an increase in E/σ_f of 50 to 100% for CD ice over EG/AD/S ice. Cracking behavior and ice-piece size can be made more realistic by adding microbubbles to sections at the top and bottom of the ice sheet only. They also note that the opaqueness of CD ice improves the viewing of cracking and under-ice movement during testing.

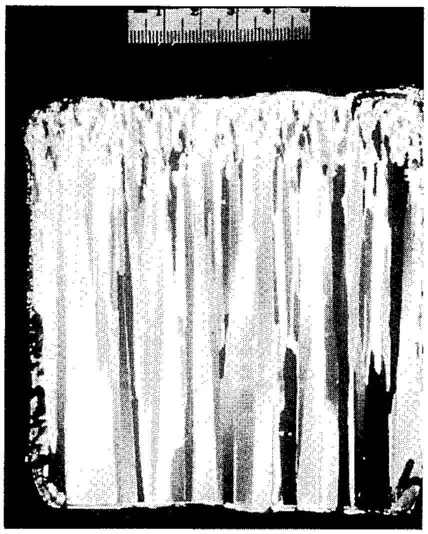

Figure 10. Urea-doped ice thin section showing the thin upper congelation layer and columnar lower layer.

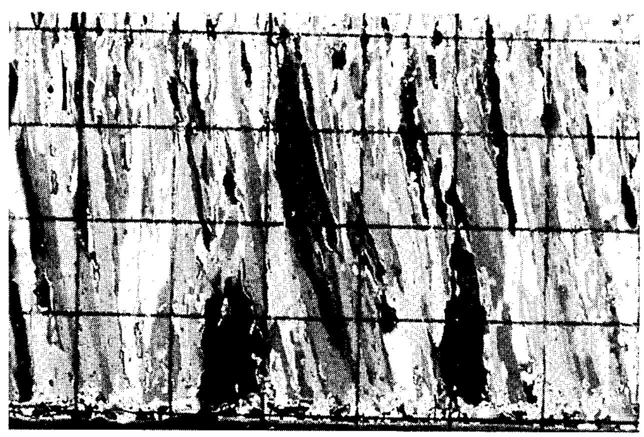

Figure 11. Thin section of EG/AD/S ice (on 1-cm grid) showing its nearly single-layered composition. (Photo courtesy of G.W. Timco, National Research Council of Canada.)

Fine-grained ice. Fine-grained model ice was developed to further improve the strength property modeling of weakened ice. A disadvantage of the urea-doped ice described above is its double-layer composition—a strong upper layer and a weaker, thicker columnar layer beneath. This composition resulted in flexure strengths about different axes that differed much more than did the flexural strengths of most full-scale ice sheets. The lower layer also resulted in some residual strength after initial breakage. An important advancement produced by fine-grained model ice is its homogene-

ity of composition and strength.

Fine-grained weakened ice is grown by continuously spraying fine ice crystals on frigid water. Recent versions of this ice are formed from dilute saline or urea solutions sprayed as a mist of fine crystals that descend on a water solution of salt or urea; the chemical additive provides additional weakening. The fine crystals form a layer that consolidates, potentially resulting in a uniform, single layer of ice (Fig. 12). For example, WARC-FG (Wärtsilä Arctic Research Centre—fine-grained) is a fine-grained ice formed on a 2% saline solution ice material that is homogeneous, brittle, and fulfills most of the strength scaling requirements. The material is grown by continuously spraying tank water (at 2% saline concentration) above an initially seeded sheet at room temperatures of –16 to –22°C. Sheets of this model ice can be grown overnight up to 70 mm thick and can be tempered to reduce strength or hardened to increase strength. Enkvist and Mäkinen (1984) report that the values of E/σ_f range between 1000 and 2000, with some values tested as high as 2480. They also report that similar results have been obtained using a 3% urea solution with the same growing technique, but that the urea provides no inherent advantage over the less costly NaCl. WARC-FG quickly became the standard model ice material for the testing program in the main test tank at WARC. Testing at this facility is primarily icebreaking by vessel and ice–structure interaction.

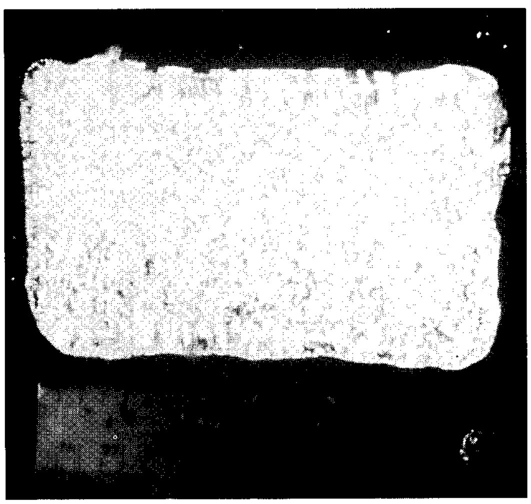

Figure 12. Thin section of fine-grained urea ice grown at CRREL.

Experience has improved WARC-FG. Nortala-Hoikkanen (1990) reports that WARC-FGX ice has better strength simulation characteristics than does WARC-FG ice. Instead of spraying a 2% saline solution, spraying now is conducted with water of saline concentration varying between 0.1 and 1.6%. This variation allows production of ice sheets of varying strength as well as thickness. The main improvements of FGX ice over FG ice are shorter growing time (30% decrease), improved cracking, and a wider range of ice strengths. The E/σ_f ratio for FGX ice is reported to vary (controllably) between 700 and 8000.

Narita et al. (1988) describe the process used to produce fine-grained urea ice at the NKK Ice Model Basin in Japan. The spraying and consolidating procedure is similar to that of the FG or FGX ice. The tank water urea concentration is held at 2.5% and the spray water concentration at 0.5 to 1.3%. This allows the tank water temperature to be brought down to –0.4°C (the approximate freezing point of the spray water yet still above the tank water freezing point) prior to seeding. The difference in concentrations of the tank and spray water prevent the growth of columnar ice at the bottom of the sheet during consolidation and tempering. While they report improved cracking and strength properties over columnar urea ice, the value of E/σ_f is given as 200 to 310.

The Helsinki University of Technology (HUT) rebuilt their 40-m×40-m ice model basin in 1989 and sought an ice material that was fine-grained and brittle to properly model icebreaker testing. Jalonen and Ilves (1990) of HUT describe their investigations of FG ice, EG/AD/S ice, EG/AD (without the sugar) ice, and EG (only the ethylene glycol) ice. Their decision to use only 0.5% ethanol as a dopant was based on a desire for a noncorrosive, nonhealth-hazardous material. The resulting GE (granular ethanol) ice is produced by continuous spraying over the basin at air temperatures of approximately –10°C. The reported E/σ_f ratio ranges from 1000 to 2000 with good cracking characteristics.

Bead ice. Belyakov (1984) describes experiments undertaken to develop a model ice for icebreaking tests in which high-density polyethylene spheres and cubes were frozen into a sheet of freshwater ice. Two methods were used in developing these hybrid ice sheets. The first method used spherical beads, 4 mm in diameter, in multiple layers that were frozen throughout the bead layer thickness. Strength properties were adjusted by varying the bead layer thickness. The other

Figure 13. Beads ice developed by Fleet Technology of Canada. (Photo courtesy of Fleet Technology of Canada.)

method entailed freezing larger-diameter spheres and cubes (or a mixture of large and small particles) up to 25 mm in diameter into the ice sheet. The sheet properties apparently can be adjusted by varying the depth of freezing. Very weak ice sheets could be formed by minor freezing right at the surface, and strong ice sheets could be formed by extending the frozen depth beyond the thickness of the spheres or cubes. Some problems in the uniformity of the properties were reported when using the cubes due to the necessity to keep the cube spacing constant. Belyakov reports flexural strengths of 25 to 400 kPa measured by the three point bending test.

Fleet Technology of Canada has introduced what it calls "beads ice" (Fig. 13). This weakened ice is produced by freezing a floating layer of plastic beads on the surface of an EG/AD/S or urea solution (Abdelnour et al. 1993) (Fig. 14). The production rate is increased and control over piece size and density enhanced. No reports of strengths are given, although mention of possible length scale factors of 5 to 50 are made. Fleet also found that material handling and bead distribution prior to freezing are important in providing a sheet with uniform properties.

Nonrefrigerated breakable ice

Several nonrefrigerated breakable model ice materials exist. Use of the most sophisticated materials is restricted by proprietary arrangements. The primary advantage of a nonrefrigerated material is that modeling does not require a refrigerated facility.

Schultz and Free (1984) describe MOD-ICE, a proprietary model ice developed by Michel and acquired by ARCTEC. MOD-ICE is prepared as a molten mixture of polyethylene powder, polyethylene beads, heavy vegetable oil, light vegetable oil, and stearic acid poured onto the water surface. Once solidified, the properties remain constant for about three days. The main improvements cited over weakened ices are increased range of E/σ_f values (1000 to 3000 even for very thin ice sheets), better crushing strength similitude, and more realistic broken piece size. Since the material can be formed in thinner, weaker sheets, the model scale can thus be increased, reducing the overall model study cost (Fig. 15).

Tryde (1975) describes a model ice material used in a study of the ice breakage pattern in front of an inclined wedge. The material is cast into sheets and includes a combination of plaster of Paris, small plastic beads, salt, borax, an air entrainment agent, and water. Tryde states that the formula can be altered to vary the material strength but that average values give an E/σ_f of 500 to 1000.

Berdennikov (1974) describes two variations of nonrefrigerated model ice material used in hydraulic model tests where the ice strength was considered important. The first consisted of keramzit (ceramic/clay construction material) grains 5 to 10 mm in diameter bonded with a cel-

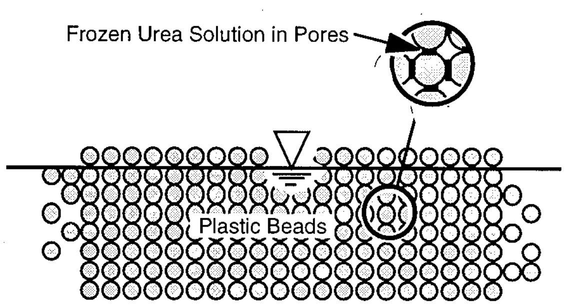

Figure 14. Cross section of beads ice, showing location of bead layer.

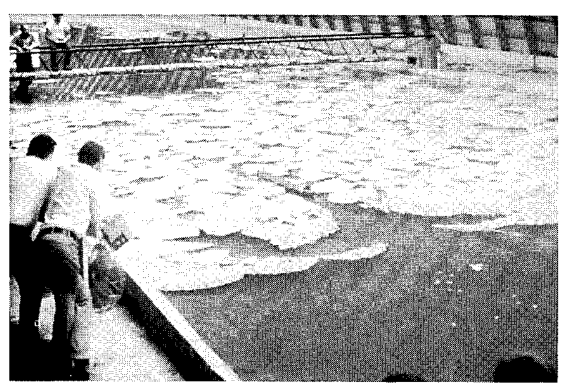

Figure 15. Physical model study using MOD-ICE.

Figure 16. Video image of SYG-ICE (foreground) fractured by an advancing accumulation of plastic blocks (upper left background).

luloid glue. This material was cast into molds 1 to 5 cm thick and upon drying had a strength (shear) of 300 to 1000 kPa. The second material consisted of expanded polystyrol beads 3 to 4 mm in diameter bonded with a lubricant grease. The strength of this material was much less, with reported values of 10 to 30 kPa.

Cowley et al. (1977) describe a model ice material developed to look at the breakup of ice sheets and accumulations due to ship passage in the St. Marys River. Polypropylene pellets, 2.5 mm in diameter, placed in the model were sprayed with an unidentified surface treatment compound. The resulting ice material reportedly gave very good qualitative results in terms of breaking, arching, and piece size. Experiments to optimize the application rate of the binder by conducting a series of punch tests are cited, but no strength values are given.

Beltaos et al. (1990) report the development of SYG-ICE, a nonproprietary model ice material developed at the National Water Research Institute of Canada to study the problem of river ice breakup. They developed this material to model a relatively weak ice cover at a reasonable model scale ($\lambda_L \approx 30$) in a nonrefrigerated environment. In their opinion, flexural strength is the most important variable influencing ice-cover breakup on a river. Modulus of elasticity is also important, because it influences deformation and the size of ice pieces. They also considered it necessary to scale the fracture toughness of ice in order to replicate ice-cover cracking. Although ice shears and crushes during cover breakup, the influences of shear strength and crushing strength are considered minor and are therefore neglected. Beltaos and his colleagues furnish a recipe for SYG-ICE (Fig. 16). It comprises a mixture of PVC resin, light exterior stucco, plaster of Paris, glass microbubbles, and water. The curing time is 10–14 days, and the model ice must be removed carefully from the molds to avoid premature breakage. They report a flexural strength of 23 to 28 kPa and an E/σ_f of about 3900. Experiments conducted on the interaction of water surges and ice jams with intact covers of their model ice material showed promising results.

SENSITIVITY OF MODEL ICE PROPERTIES

The material properties of many model ice materials change with time, due to temperature effects, handling procedures, degradation, and other factors. Even the very stable materials (e.g., plastic beads) can develop a bio-growth over time that may vary the surface tension or angle of internal friction of the material. The plastic materials could be abraded or fractured by continuous cycling through a pump, which would also change the bulk properties. The properties of breakable ice materials are especially time- and temperature-dependent. Temperature has a large effect on the bending and shear strength of refrigerated materials. Ensuring uniformity of material properties and comparison of results between tests can be difficult when using refrigerated materials. While some of the nonrefrigerated synthetic materials extend the working period of ice sheets from hours to days, continued sampling must be done to ascertain the change in material properties with time.

Uniformity of model ice properties is an important modeling concern, especially for breakable ice covers. Care must be taken in the cover formation process to assure uniform freezing and thickness of refrigerated sheets and uniform consistency and thickness of nonrefrigerated ice materials. Placement of particulate model ice materials, like beads, may result in nonuniform thickness or porosity. Nonuniform material properties may result in cover failure at weak points, overestimation of thickness, improper piece size, and so forth. Careful sampling prior to testing should be carried out to ensure uniformity.

SUMMARY

Table 3 was prepared to aid in selection of model ice. It suggests choices of model ice material to suit the primary process to be modeled. For example, if only the shear stress or drag of the underside of an ice cover is of interest, then almost any model ice material could be used. For most applications, unbreakable sheets of buoyant material (e.g., plywood or Styrofoam) with additional roughness are the easiest to use in terms of cost and handling during experimentation. If the process involves shoving and thickening of an evolving ice jam, material choices become more con-

Table 3. Summary of modeling tasks and appropriate model ice materials.

Modeling task or property	*Suitable model ice material choices*
Water velocity profiles	RS, BR, PB, (RIN, RIFG, NRS)[1]
Ice movement	BR, PB, (RIN, RIFG, NRS)[2]
Ice–shore interaction	PB, (RIN, RIFG, NRS)[3]
Ice thickness	RS, BR, PB, RIN, RIFG, NRS[4]
Ice jam thickness	PB, (RIN, RIFG, NRS)[5]
Ice jam evolution and movement	PB, (RIN, RIFG, NRS)[5]
Ice sheet deflection	RIN, RIFG, NRS
Ice cover breakup	RIN, RIFG, NRS
Ice breaking	RIN, RIFG, NRS
Ice–structure interaction	RIN, RIFG, NRS

RS – Rigid sheet (plywood, Styrofoam, etc.)
BR – Blocks and random shapes (wood, plastic, wax, etc.)
PB – Plastic beads and other particulates
RIN – Refrigerated ice (freshwater, urea-doped, saline-doped)
RIFG – Fine-grained refrigerated ice (FGX, EG/AD/S, etc.)
NRS – Nonrefrigerated sheet mixtures
1 – Flowing water beneath the sheet may change roughness characteristics with time
2 – Assumes that sheet has been broken into pieces
3 – Assumes movement along shore and sufficiently broken pieces
4 – Generally controlled by scaling factor
5 – Assumes sheet has been broken into sufficiently sized pieces

Table 4. Ice strength properties of model ice materials.

Model ice material	*Flexural strength (kPa)*	*Elastic modulus flex. strn.*	*Compressive strength (kPa)*	*Shear strength (kPa)*	*Specific gravity*	*Static coeff. of friction (ice–ice)*
Sea ice (cold)	700–800	2500–4500	8K–12K (v)	1500–2100	0.91	0.45–0.5
Freshwater ice	500–1500	1500–6000	10K (v) 1.5–3K (h)	700 (v) 1200 (h)	0.92	0.5–0.7
Saline-doped	20–80	1000–1700	100–275 (v) 75–180 (h)	40–85 (v) 45–110 (h)	0.89	0.45
Urea-doped	20–120	1000–2500	120–250 (v) 75–160 (h)	30–70 (v) 35–65 (h)	0.93–0.94	0.35
WARC-FG	20–75	1000–2000	50–400 (v)	10–45	0.89	0.45
FGX	15–90	700–8000	15–180	10–45	0.88–0.91	NR
Urea, fine-grained	15–45	200–310	10–45	NR	0.92	NR
EG/AD/S	20–100	1500–2500	150–370 (v) 80–280 (h)	NR	0.93	NR
CD ice	NR	2200–3400	NR	NR	0.83–0.93	NR
GE ice	15–90	1000–2000	15–55	NR	NR	NR
MOD-ICE	10–80	700–3000	12–82 (h)	7–120	0.70–0.89	NR
Plaster of Paris	100–200	500–1000	500–1000 (h)	250–500 (v)	0.94	NR
SYG-ICE	23–28	3900	62 (h)	7 (v)	0.90	0.50

(v) and (h) signify vertical and horizontal directions, respectively.

strained. Other factors, such as availability of refrigerated space, material handling requirements, and cost must also be considered in the final determination of which material to use.

Table 4 summarizes ice strength properties of several model ice materials as well as ranges for freshwater and sea ice.

A parting comment: Physical modeling is an art partially supported by physics. Few things in the practice of the art are sacred. The modeler's skill in interpreting a model and obtaining the necessary results are often more important than strict adherence to similitude.

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Physical modeling is often used to study complex ice processes when analytical formulations or numerical simulations fall short. Judicious choice and use of materials to model the ice in scaled experiments requires knowledge of the properties of the material as well as an understanding of the dominant forces governing the process to be modeled. This report describes general similitude requirements for various modeling situations and the properties of several previous and currently used model ice materials.

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